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Seismic P-, SH- and SV-wave cross-hole testing using direct-push technology for the determination of geotechnical parameters

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ABSTRACT

Seismic surveys are often carried out between two or more pre-installed boreholes to assess unknown geological situation in the subsurface with high resolution. However, the cost of installing boreholes is often a budgetary constraint. Therefore, the direct-push technology, where rods are pushed into the subsurface, seems to be a more suitable tool and by incorporating seismic sources and receivers into the push rods, geophysical methods can become more flexible and adaptable, especially for larger areas of investigation or sites in harsh environments. In this paper, we present field results using such a direct-push seismic system as a cost-effective alternative to standard borehole-based investigation techniques. For both techniques complete cross-hole datasets of P, SV and SH waves were acquired at two different test sites (1) between direct-push boreholes and (2) between PVC cased boreholes. The in-situ profiles of the paired shear wave velocity profiles (SH and SV) were used to evaluate the stress history of the soils by deriving the over-consolidation difference (OCD). Many geotechnical parameters are influenced by the soil stress history, such as deformation properties and soil stiffness, but in the calculation of geotechnical parameters, such as the lateral stress state (K_0), consolidation coefficient and liquefaction response the OCR also plays an important role. The tests also showed that direct-push based techniques make even seismic methods more flexible as test positions can be easily adapted and changed according to the results, local conditions or client requirements.

Keywords: Cross-hole, direct-push, P-, SH- and SV dataset, geotechnical parameters, over-consolidation ratio, (OCR), lateral stress (K_0)

1. Summary

Seismic shear waves primarily provide information on the shear stiffness and elastic properties of the soil, rather than directly indicating the soil stress history and the state of over-consolidation. However, depending on the different static stress states of a soil, SH and SVwaves have individual site specific velocities and can be used to estimate over-consolidation and at rest lateral stress conditions.

Different cross-hole experiments were carried out to measure the paired shear wave velocity profiles (SH and SV) which allows the determination of geotechnical parameters using the empirical relationships reported by Ku and Mayne (2013, 2014). The first test is a conventional cross-hole test using two standard PVC cased boreholes and as a second experiment a cross-hole test between a previously installed PVC cased borehole and the direct-push borehole was done.

The results of both experiments show that the direct and accurate in-situ determination of OCR and K_0 using SH and SV waves provides a valuable tool to evaluate the dimension of these geotechnical parameters but is limited to some extent. Careful interpretation and correlation to other geotechnical test data (lab testing) is required.

1.1. Introduction

Both types of seismic shear waves (horizontally polarized shear waves (SH) and vertically polarized shear waves (SV) have directional and polarization characteristics (Roesler, 1979). SV and SH waves with orthogonal displacement vectors cause rock particles to vibrate perpendicular to the direction of wave front motion.

Both shear waves are sensitive to changes in dynamic soil parameters such as shear strength or Young's modulus. Understanding the characteristics of SH and SV waves is essential for seismic analysis, site response studies and for assessing the behavior of soils and rocks during earthquakes.

By analyzing SH and SV wave properties, geotechnical engineers and geoscientists can assess the potential for soil liquefaction, e.g. during earthquakes; calculate the shear modulus and material damping for site response analysis; analyze the depth-oriented variability to identify different soil layers, including soft soils, stiff soils and rock formations; and estimate important geotechnical parameters such as shear strength, modulus of elasticity and Poisson's ratio. This knowledge is essential for the design of safe and reliable geotechnical structures in seismically active areas. An overview about the derivation of geotechnical parameters from seismic data is given in Fig. 1.

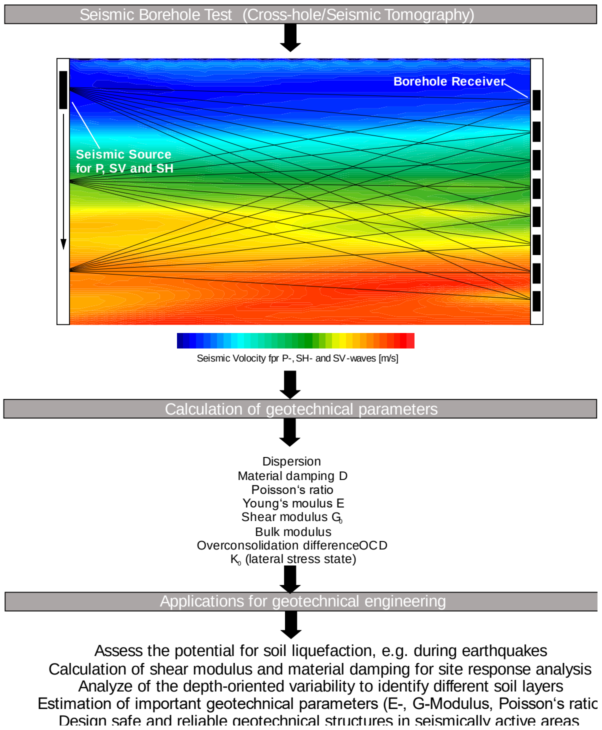

Figure 1. Calculation of geotechnical parameters from seismic velocities and typical application in geotechnical engineering.

1.2. Geotechnical parameters

An important geological process is the exposure of soil to different loading conditions during its formation or later history. This includes loading during sedimentation, increasing load during glaciation, static loading from structures, lowering of groundwater levels or even desiccation. Depending on the soil type, these conditions persist and affect the propagation of seismic waves, especially the two different types of shear waves (SH and SV). In geotechnical engineering, the stress history of the soil is described by the over-consolidation ratio ($OCR = \sigma'p / \sigma'vo$) or over-consolidation difference ($OCD = \sigma'p - \sigma' vo$). The OCR is defined as the ratio between the maximum overburden stress that the soil has ever experienced $\sigma'p$ (i.e. an ice cap covers the soil) and the current overburden stress $\sigma'vo$ (i.e. melting ice cap). It allows the characterization of the stress history relative to the maximum stress history of the soil in the past. A soil is considered to be over-consolidated ($OCR>1$) if the current effective vertical stress is lower than the maximum stress it has experienced in the past, resulting in a higher shear strength and stiffness than would be expected from its current effective stress state. The magnitude of OCR is essentially constant with depth.

OCR affects the shear strength, compressibility and permeability of a soil and is therefore an important parameter in geotechnical engineering. For example, over-consolidated soils tend to have higher shear strength and stiffness than normally consolidated soils, making them more resistant to deformation and settlement. However, over-consolidation can also result in higher permeability due to the presence of cracks and fissures in the soil. Soil deformation is also greater in normally consolidated soils than in over-consolidated soils.

The over-consolidation ratio is typically determined by laboratory tests or by analyzing the results of in-situ tests, such as flat dilatometer (DMT) or pressuremeter tests (PMT). Determining the OCR using seismic shear waves is not straightforward and can be challenging. However, seismic methods can indirectly contribute to the estimation of OCR by providing data on other geotechnical parameters, such as small-strain shear modulus (G_0) which is correlated with consolidation and stress history. The Shear modulus or soil stiffness is one of the most important parameter needed for soil characterization. The shear modulus describes the deformation of the soil that occurs when a force or load is applied. It is the product of bulk density and shear wave velocity squared. There are several types of geotechnical engineering problems with dynamic loading: machine vibrations, seismic loading and liquefaction. Mostly, the mechanical properties of soil control the response of soils to cyclic loadings. Seismic is a sufficient method to analyse these dynamic soil properties.

Mackens et al. (2017) used the empirical relationship reported after Ku and Mayne (2014) based on data from uncemented geomaterials and used the directional characteristics of shear waves to assess the stress history using the OCD value. The OCD is the over-consolidation difference and it is related to the over-consolidation ratio, refer to “Eq. 1”.

The OCD is strongly correlated to the paired stiffness ratio ($G_{0,HH}/G_{0,VH}$). With this empirical relationship, shear wave velocity measurements (Vs) can directly be used to determine the small strain shear modulus (G_0) and to calculate the over-consolidation difference assuming a transverse isotropy along the vertical axis ($Vs_{,VH} = Vs_{,HV}$). In addition, the at rest lateral stress coefficient K_0 is a fundamental parameter especially for geotechnical design problems. It represents the anisotropic geostatic stress state and the ratio of horizontal stress to vertical stress in a soil or rock mass under undrained conditions, specifically when the soil is in a state of rest or equilibrium (Ku and Mayne 2013). In general, the K_0 is defined as the ratio of the effective geostatic horizontal stresses σ'_{ho} to the effective vertical stresses σ'_{vo} at rest.

While K_0 is considered to be a constant quantity at initial loading, the lateral stress coefficient under unloading or reloading is dependent on the over-consolidation and can be described as a function of the OCR. Several functions that take into account the initial decrease in lateral stress can be found in the literature (e.g. Bellotti et al. 1975, Breth et al. 1978). An empirical relationship using paired shear wave velocity data has also been reported by Ku and Mayne (2013).

It is important to recognize that K_0 for over-consolidated materials (K_0 =0.5-1.0) is not a constant value and may vary depending on site-specific conditions and soil properties such as stress history, soil composition, degree of over-consolidation, magnitude of the current effective vertical stress applied and the presence of anisotropy. In particular, the assessment of soil reloading is essential for improving foundation performance, accelerating consolidation processes, verifying design assumptions and evaluating the long-term behaviour of geotechnical structures.

1.3. Standard Cross-hole field experiment

The first test example shows the use of measured SH and SV waves using a cross-hole experiment and P-wave tomography measurements for geotechnical evaluation at a test site near Munich/Germany. The geology consists of more or less alternating clayey-silty and sandy layers according to the available borehole profiles.

A cross-hole test was carried out using the BIS-SV and the BIS-SH borehole sources to obtain data for SH and SV wave data up to a depth of 70 m. The novel BIS-SV source generates highly reproducible vertically polarized shear waves (SV) with large amplitudes. No special alignment of the source, such as rotation, is required, improving the practicality of S-wave measurements. The BIS-SV is now part of the triplet of sources that works with both the high-voltage impulse generators IPG800 and IPG5000. All sources and the borehole geophone are coupled to the borehole wall by a pneumatic clamping system (inflatable bladder). P-wave tomography up to a depth of 50 m was carried out using the high-voltage sparker source SBS42 and a hydrophone string with 24 channels and a sensor spacing of 1 m. For this experiment, the seismic sources were placed in one borehole and the receivers were placed in the other borehole at a distance of about 10 m.

For further analysis, the first arrival traveltimes for all wave types (P, SH and SV) were picked. 80% of the SV data and 72% of the SH data had a pick accuracy of less than 5%. The velocities of the vs, VH and vs, HV were calculated from the measured SV- and SH-traveltimes using the distance and the measured borehole deviation data. The acquired cross-hole records with picked first arrival times for P-, SH- and SV waves and their calculated velocities are shown in Fig. 2 while the P-wave tomogram is displayed in Fig. 3.

At a depth of about 12 m a strong increase in seismic velocity was observed for the P-wave and both S-waves. The P-wave increases to values above 1500 m/s, presumably due to the transition to the saturated groundwater zone, while the S-wave increases from about 300 m/s to about 600-700 m/s in the same depth range. From about 12 m depth downwards the velocities increase continuously, alternating areas of lower seismic velocity with zones of higher seismic velocity. This is observed for P-wave, clearly visible in the P-wave tomogram and also for the S- waves. The P-wave varies between 1800 m/s and 2500 m/s, which is very high for the sedimentary material most likely due to high compaction. The S-wave velocity increases from about 600 m/s to about 900 m/s.

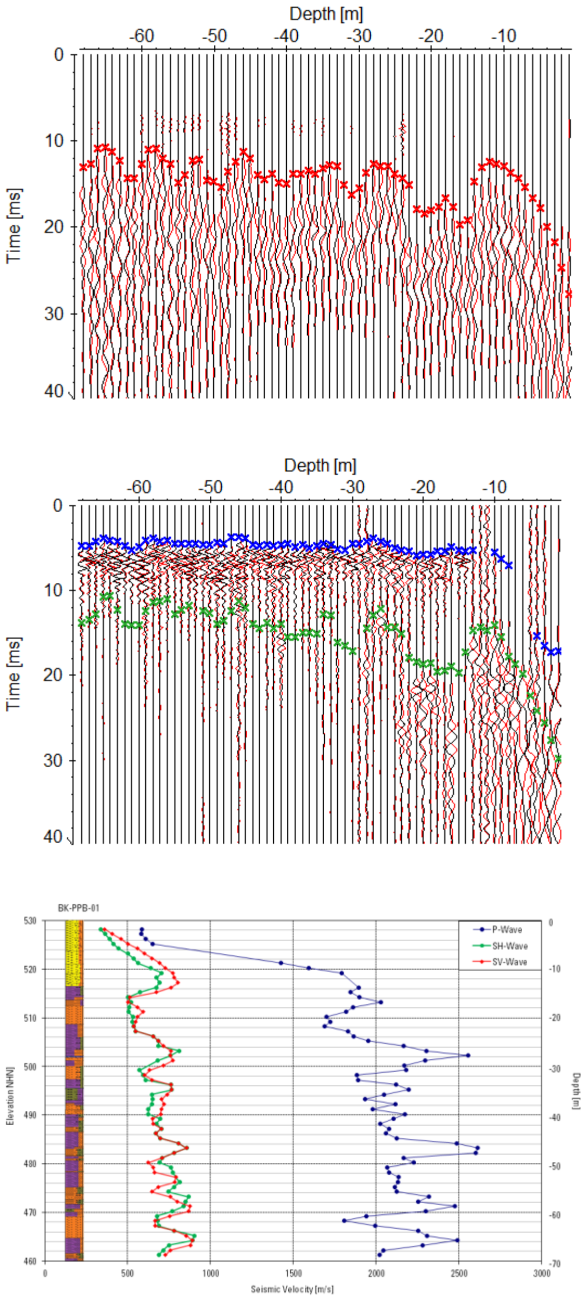

Figure 2. Above: Cross-hole dataset with picked arrival times for P- (blue crosses), SH- (green crosses) and SV-waves (red crosses). Below: Cross-hole P- (blue line), SH-

(green line) and SV-wave (red line) velocities with depth.

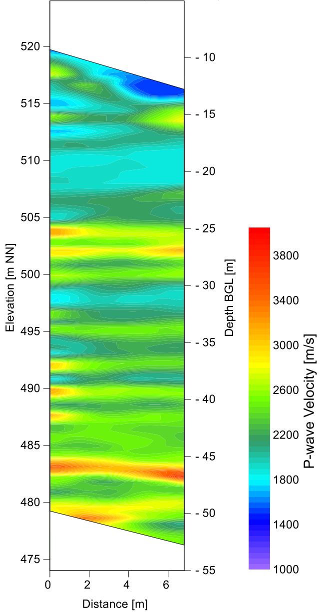

Figure 3. Calculated P-wave tomogram.

With the paired shear wave velocity profiles (SH and SV), the over-consolidation difference (OCD) and the at-rest lateral stress coefficient K_0 were also determined using the empirical relationships of Ku and Mayne (2013, 2014). The OCD is related to the over-consolidation ratio by "Eq. 1":

$$\boldsymbol{OCR} = (\boldsymbol{OCD} + \boldsymbol{\sigma'_{vo}})/\boldsymbol{\sigma'_{vo}} \qquad (1)$$

with σ'_{vo} as the current effective overburden stress. For the calculation of the OCD a density of sand equal 2000 kg/m^3 is used.

From Fig. 4 it can be observed that there are three zones in particular that are strongly over-consolidated, while the K_0 value determined with a good first order approximation indicates that the whole profile has K_0 >0.5, indicating over-consolidation. Further analysis is required to explain this result in more detail.

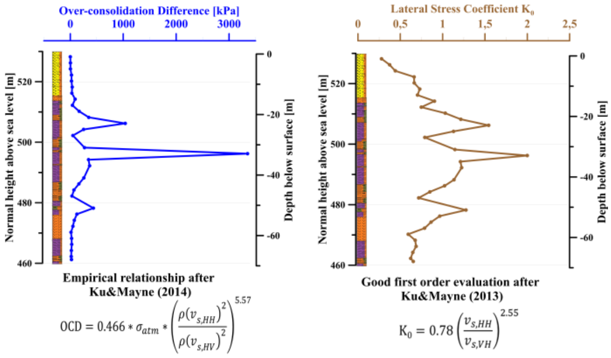

Figure 4. Determined (a) over-consolidation difference (OCD) and (b) the at rest lateral stress coefficient K₀.

1.4. Cross-hole field experiment using direct-push technology

The second field test was a direct-push based cross-hole field experiment. It was conducted in July 2016 at the test site for Technical Safety (TTS) of the Federal Institute for Materials Research and Testing (BAM) in Horstwalde, Germany, to demonstrate the direct-push based crosshole technique and its general applicability. The TTS is a general validation facility for various investigation purposes and techniques so that the geological and geotechnical soil conditions are well-known. This area is dominated by post glacial sediments, mainly medium sands with some fine sand at the top and coarser material at the bottom.

The experiment was carried out between a previously installed standard 3" (ID) PVC cased borehole and a direct-push borehole which is effectively a steel rod with an inner diameter of 77 mm that is pushed into the underground using high-frequency (sonic) vibrations and the weight of the mobile platform (Geoprobe). The distance between the two boreholes was 5 m and the measurements were made in a depth from 4 to 10 m with a measuring interval of 1 m. To generate seismic signals two different borehole sources were used. The borehole source type BIS-SH generates mainly SH-waves but also a good amount of P-waves. To generate SV-waves the borehole source type BIS-SV was used. Both sources operate in a similar way, a solenoid is activated by high-voltage and pushes either a copper plate against the borehole wall to generate a SH-wave impact or pushes the plate upwards and downwards to generate SV-waves. During operation the source was placed in the PVC-cased borehole and pneumatically clamped to the borehole wall. Seismic signals were received by the Multi-Station Borehole Acquisition System (MBAS), a 10-station 3C digital acquisition system with station spacing of 1 m, placed and clamped in the steel rod.

Seismic raw data were compared for different source and receiver configurations. It was expected that the signal quality would depend on the test setup and configuration as the source and receiver coupling and transmission conditions may differ from PVC casing to steel rod.. In general, higher amplitudes (better signal-to-noise ratio) for S-waves can be observed when the borehole source is placed in the PVC cased borehole compared to the reverse positioning of the borehole source in the steel rod. The polarization of the S-waves appears to be little or not affected by the type of casing (PVC or steel). In general, however, the results show that both of the tested source and receiver configurations can be used to obtain a data set of P-, SH- and SV-waves with a good quality.

For further analysis the first arrival traveltimes for all wave types (P, SH and SV) were picked for each cross-hole source and receiver configuration and the velocities were calculated based on source and receiver distances.

In general, the velocities for the P-waves vary only slightly between 1580 and 1680 m/s whereas the variation for the S-waves is much higher and between 140 and 300 m/s (Fig. 5). Above 7 m, there is an increase in velocity for all wave types. P-wave and especially S-wave velocities do not vary much at depths between 7 and 13 m and are lower compared to the seismic velocities in the upper layer. The sediments below 7 m are dominated by a poorly graded medium sand with only a small amount of coarser grain sizes showing low resistance values which indicate a low compactness of the soil. In contrast, the seismic velocities increase significantly in the upper layer above 7 m. This layer consists of well graded sand which contains particles of a wider range of grain sizes. This results in higher cone resistance values and indicates a higher degree of compactness.

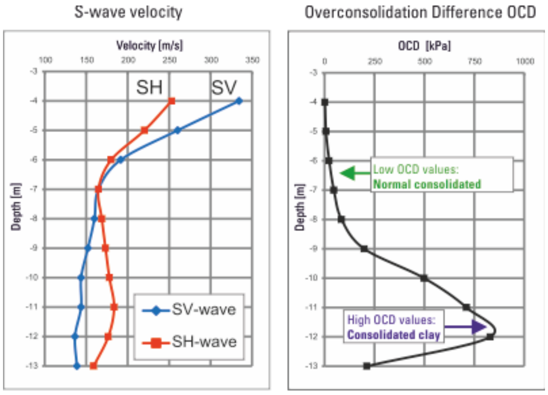

Figure 5. The depth velocity profiles of SH-and SV-waves from the direct-push based cross-hole test (left) and over-consolidated difference OCD (right).

We can also observe a velocity separation of SV and SH waves. While SV wave velocities are marginally higher than SH waves in the upper layer, the opposite is observed in the deeper part below 7 m, where SH waves travel faster than the SV waves (Fig. 5). The directional characteristics of the shear waves are useful for evaluating the stress history in soils in terms of the over-consolidation ratio (OCR) (cp. Chapter 1.3). The calculated values of the over-consolidation difference (OCD) show a maximum of about 40 kPa for the upper layer (Fig. 5). This corresponds to a G_0 stiffness ratio ($G_{0,HH}/G_{0,HV}$) < 1. In contrast, the OCD values increase significantly below a depth of 7 m, reaching around 100 - 800 kPa. These rather high values are correlated with the noticeable shear wave velocity difference of $Vs_{,HH} > Vs_{,HV}$ indicating a G_0 stiffness ratio ($G_{0,HH}/G_{0,HV}$) > 1. According to Ku and Mayne (2014), the lower OCD values calculated for the upper layer are characteristic for normal consolidated sand. The unusually high values in the lower sandy layer are more typical for over-consolidated clay and indicate that the soil has experienced a higher pre-consolidation stress compared to the current effective overburden stress. The SH/SV velocity ratio observed at the TTS test site is therefore indicative of anisotropic material behavior due to pre-consolidation during the geological history. However, this soil behavior is controversially discussed, i. e. whether non-cohesive sandy soils can store a permanent deformation induced by primary loading (Kindler 2016).

2. Conclusions

Depending on the different static stress states of a soil, the SH- and SV-waves generated by a cross-hole test will have individual site-specific velocities and can be used to evaluate the dimensions of over-consolidation and at-rest lateral stress conditions. From an economical perspective the number of boreholes for geophysical investigations, such as down-hole, cross-hole and tomography testing is limited due to high borehole installation costs. Therefore, we proposed an alternative to conventional drilling by using the direct-push technique in combination with seismic cross-hole measurements. It is shown that the method is sufficient to measure geotechnical relevant parameters such as the G_0 stiffness ratios and thus values of OCD in order to evaluate the soil stress history based on the directional characteristics of the shear wave.

The newly developed BIS-SV source which generates a highly reproducible vertical shear wave with high signal amplitudes, allows the determination of the OCD from the paired shear wave velocity profiles measured in-situ. The OCD is an important parameter in geotechnical engineering for assessing the stability, settlement behavior, and potential for ground failure potential in soil layers. Seismic shear waves primarily provide information on the shear stiffness and elastic properties of the soil, rather than directly indicating the past stress history and the state of over-consolidation. The at-rest lateral stress coefficient, K_0, is associated with the lateral pressure exerted by the soil on its boundaries in the absence of external loading or disturbance and represents the lateral stress state of the soil when it is allowed to freely adjust and reach a state of equilibrium under its own weight.

To achieve a more accurate determination of OCR and K_0 using seismic methods, it is common to combine seismic data with other geotechnical information and empirical correlations. It is important to note that the accuracy of OCR and K_0 determination using seismic shear waves depends on several factors, including the complexity of the subsurface, the quality and resolution of the seismic data, the applicability of empirical correlations, and the expertise of the geotechnical engineer or geophysicist involved in the analysis.

3. References

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